TEV EMISSION FROM CLOSE BINARIES

I.V.MOSKALENKO*
International Centre for Theoretical Physics,
Trieste, Italy

Abstract. It is commonly accepted that candidates for very high energy γ-ray sources are neutron stars, binary systems, black holes etc. Close binary systems containing a normal hot star and a neutron star (or a black hole) form an important class of very high energy γ-ray sources. Such systems are variable in any region of the electromagnetic spectrum and they enable us to study various stages of stellar evolution, accretion processes, mechanisms of particle acceleration etc. Phenomena connected with this class of very high energy γ-ray sources are discussed. Particular emphasis has been placed on the TeV energy region.

1. Introduction

The history of very high energy (VHE) γ-ray astronomy goes back to the 1960s, when small groups beginning with small experiments developed the ground-based techniques that have been used for the next thirty years. The discovery of photons of TeV energy (and above) from the directions of the Crab Nebula (Fazio et al. 1972) and Cygnus X-3 (Vladimirskii et al. 1973) in the early 1970s has aroused the active development of VHE γ-ray astronomy in the 1980s. It became possible due to new techniques and new methods of data-analysis, based on the suggestion that the predominant TeV emission is periodic. During the last decade there have been a number of exciting discoveries of new VHE γ-ray sources. Among these the detection of VHE γ-rays emitted by X-ray binaries represents one of most interesting achievements of ground based γ-ray astronomy. Although reports of experimental groups are often in conflict, at least four binary systems, sources of TeV photons (Cygnus X-3, Hercules X-1, 4U115+63, Vela X-1) seem well-established.

The importance of X-ray binary systems for the development of modern physics is beyond question. Such objects present natural laboratories for studying the fundamental properties of matter in extreme physical conditions. These are: the strong magnetic and gravitational fields in the vicinity of a neutron star, the large amounts of mass transferred from a normal companion to the neutron star, and the neutron star itself at last which presents a bulk of matter in a state unattainable in terrestrial laboratories. Moreover, as it is became clear since the detection of TeV γ-rays, such fast rotating degenerate stars are powerful accelerators of particles up to energies well exceeding those of man-made machines.

* On leave from Nuclear Physics Institute, Lomonosov State University, 119 899 Moscow, Russia (e-mail: imos@taspd.npi.msu.su)

During the thirty years of the space astronomy era, thousands of papers have been devoted to the physics of X-ray binary systems. No one can give a complete description of the achievements in this field in a single paper. For this reason the reader is referred to a number of excellent books and reviews. Evolution of X-ray binaries, their phenomenology, mechanisms driving the mass transfer were extensively discussed by, e.g., Shakura & Sunyaev (1973), Pringle (1981), Bradt & McClintock (1983), Shapiro & Teukolsky (1983), Joss & Rappaport (1984), more recent Hunt & Battrick (1989), Bhattacharya & van den Heuvel (1991), Lewin et al. (1993), very extensive references can be found in Aslanov et al. (1989). A large amount of new data was obtained with X-ray satellites (Nagase 1989; van der Klis 1993), and ground-based technique in TeV and PeV γ-rays (e.g., see reviews by Protheroe [1987], Chadwick et al. [1990], Fegan [1990], Vacanti [1990], Weekes [1988, 1992]). A special issue was devoted to Cyg X-3 (Bonnet-Bidaud & Chardin 1988). Many topics of astrophysics of cosmic rays and γ-astronomy in general have been covered in a book by Berezinsky et al. (1991).

The aim of this work is to give a critical analysis of results related to one kind of VHE γ-ray sources: close binary systems. The paper is organized in the following way. In section 2 we overview processes in X-ray binaries in general. Observed properties of several X-ray binary systems are briefly discussed. Section 3 is devoted to models for VHE γ-ray production. Propagation of VHE γ-rays from the site of their production to an observer is considered in detail in section 4.

The following terms are generally accepted in γ-ray astronomy. The term TeV is common to denote the energy region within $\sim (0.1 - 100) \times 10^{12}$ eV and the term PeV stands for the region $\sim (0.1 - 100) \times 10^{15}$ eV. Besides, the term very high energy (VHE) usually denotes the energies, accessible to the atmospheric Cherenkov technique ($\sim 0.1 - 10$ TeV) and is used in the same meaning as the TeV term. Energies above 100 TeV, where particle detector arrays are used, are related to ultra high energies (UHE).

2. X-Ray Binary Systems

2.1 A General View

X-ray binary systems containing a neutron star and a normal hot star form a considerable proportion of objects reported as TeV and PeV sources (Table I). Two broad classes of X-ray binaries can be distinguished. In high-mass X-ray binaries, the early-type companion star, typically an OB supergiant, has a mass in excess of $10M_\odot$. Low-mass X-ray binaries contain a companion with a mass below $1M_\odot$, which may be a main-sequence star, a white dwarf or a red giant.

Several X-ray binaries are schematically shown in Fig. 1. Most of X-ray binaries has well-defined orbits, that allows us to analyze and interpret observational data. An effective way to determine the orbital parameters of such a binary system is to measure the orbit of an X-ray pulsar by tracking its X-ray pulses (Joss & Rappaport 1984), although the parameters obtained by various authors still differ. Orbital parameters of several binaries determined by this mean (exception: Cyg X-3) and temperatures of the visible companions obtained using their spectral classes (Bradt & McClintock 1983; Allen 1973) are summarized in Table II.

The X-ray luminosity of such systems is derived from the gravitational potential energy that is released near or on the surface of the neutron star by the infalling gas. The power developed by matter falling into a gravitational potential is given by $L = GM\dot{M}/R_{ns}$, where G is the gravitational constant, $\dot{M}$ is the mass accretion rate, M is the mass of the neutron star, and R_{ns} is its radius. For a typical neutron star the energy liberated (in a steady state) is of the order of 10% of the rest mass energy of the infalling material. For sufficiently high mass accretion rates ($\dot{M} \approx 1.5 \times 10^{-8} M_{\odot}$ yr^{-1}) the energy released approaches the Eddington limit at which radiation pressure balances gravity ($L \approx 1.3 \times 10^{38} [M/M_{\odot}]$ erg/s, in the case of the spherical symmetric accretion).

X-ray binaries tend to show very different behaviour, defined primarily by the mass transfer processes (Bhattacharya & van den Heuvel 1991). Wind-fed systems have relatively low X-ray luminosity (Vela X-1, GX 301-2, 4U 1538-52) apart from disk-fed systems (Sco X-1, Her X-1, Cen X-3, 4U 0115+63), which indicate luminosities one order of magnitude higher and even super-Eddington luminosities (LMC X-4 and SMC X-1), see Table III.

Early-type stars lose considerable amounts of matter in the form of a stellar wind. A small fraction $\sim 10^{-5}$ of the wind mass flux captured by the neutron star is sufficient to yield a $2 \times 10^{35} - 2 \times 10^{36}$ erg/s X-ray source. Mass accreted from a stellar wind has a low angular momentum so that a permanent accretion disk is unlikely to form. The X-ray luminosity in such systems is very sensitive to small fluctuations in the wind velocity. Their orbits are relatively wide and have considerable eccentricities. These systems contain the X-ray pulsars with long pulse periods, of the order of hundreds of seconds, which show alternating spin-up and spin-down episodes.

In more close binaries the companion star approximately fills its critical potential lobe (Fig. 2), that allows gas to escape from its surface near the inner Lagrangian point and to flow towards the neutron star. Matter transferred in this way carries a considerable amount of angular momentum with respect to the compact object, and forms a large ($R \sim 10^{10} - 10^{11}$ cm), optically thick accretion disk. The viscous forces in the gas cause it to fall slowly on the neutron star. Her X-1, Cen X-3, LMC X-4, and SMC X-1 show clear evidence for the presence of a sizable accretion disk indicated by optical, UV, and X-ray observations. The accreting matter transfer its angular momentum, which results in a continuous shortening of the pulse period. These systems have shown trends of the spin-up phenomenon and have short pulse periods.

In this picture there are no indications that X-ray binaries might also be sources of cosmic rays and/or VHE γ-rays such as have been observed. It is only apparent that the VHE radiation is associated with charged particles, whose individual energies exceed the energy of the observed gammas. There is not yet firm theoretical understanding how these particles might reach ultra-high energies, but models include the use of huge potential drops resulting from the unipolar induction mechanism operating in an accretion disk (Chanmugam & Brecher 1985; Cheng & Ruderman 1989, 1991) and shock acceleration (Eichler & Vestrand 1985; Kazanas & Ellison 1986; Kiraly & Meszaros 1988). The γ-rays are produced through interactions of the beam with matter in the binary system. The same object may also be a source of other kinds of high-energy particles, such as neutrons and neutrinos.

We shall now discuss briefly data on several X-ray binaries reported as TeV sources, which are mostly shown in Fig. 1. For a comprehensive analysis of the data we refer to numerous reviews cited in the Introduction.

2.2 Vela X-1, GX 301-2, 4U 1538-52

Satellite X-ray observations of wind-fed systems, showing that absorption varies strongly with orbital phase, imply that winds from companions are not quite spherically symmetric. Intervals of high absorption accompanied by an excess in low-energy X-ray radiation, as compared to what is expected from photoelectric absorption by cold material (Haberl 1991a). Such high-density regions can be quite extended in angle in the orbital plane, but they may not extend far above the orbital plane, and they may be filamentary in nature (e.g., Blondin et al. 1990).

Vela X-1 and GX 301-2 show similar behavior. Exceptionally high absorption in Vela X-1 was observed by *EXOSAT* (Haberl & White 1990) near phases 0.3 and 0.5 (phase 0 corresponds to the mid-eclipse), and is also evident in the 1983 *Tenma* spectra (Nagase 1989). Increases in the absorbing column density last from minutes to many hours. Modelling calculations show that it can be explained qualitatively by absorption and scattering in high-density regions, which appear as an accretion wake or a gas stream, originating at the inner Lagrangian point and trailing behind the neutron star (Haberl & White [1990], Haberl [1991a], see also Lewis et al. [1992] and references therein). Perhaps, such a gas stream trails the neutron star without being accreted.

In the case of GX 301-2 simple spherical symmetric models also failed to reproduce its X-ray light curve. However, it could be explained with a dense gas stream from the companion trailing the X-ray source (Haberl 1991b). Due to the variable orbital velocity, the neutron star moves twice through the spiral-shaped gas stream causing a strong excess in low-energy X-rays near phase 0.7, when the neutron star lies in front of the companion, and a second broader maximum around phase 0, which corresponds to the neutron star lying behind the companion. An inhomogeneity in the stellar wind can explain also episodes of increased absorption of X-rays in 4U 1538-52 (Robba et al. 1992).

Persistent emission of VHE γ-rays from Vela X-1 is well established (Chadwick et al. 1990), apart from GX 301-2 and 4U1538-52 for which no evidence for TeV/PeV emission has been yet found. The orbital modulation is weak (Raubenheimer et al. 1989), there are also strong outbursts throughout the binary orbit. Episodes of enhanced emission have been observed at energies ranging from TeV to PeV at phases 0.68 ($\geq$ 0.3 TeV, Bowden et al. [1992a]), ≈ 0.51 ($\geq$ 110 TeV, Suga et al. [1987]), ≈ 0.13 ($\geq$ 800 TeV, van der Walt et al. [1987]), and $\approx 0.50 - 0.54$ ($\geq$ 3000 TeV, Protheroe et al. [1984] and Meyhandan et al. [1992]). As an example, Fig. 3 shows data collected by the Potchefstroom group.

2.3 Cen X-3, SMC X-1, LMC X-4

Other group of massive X-ray binaries, Cen X-3, SMC X-1, and LMC X-4, has almost circular orbits and indicate a trend of the neutron star to spin-up. These binaries show a noticeable rate of the orbital period changes (Kelley et al. 1983; Deeter et al. 1991; Levine et al. 1991, 1993) due to the tidal interaction. Optical observations of the companions have shown that the X-ray source has an accretion disk that is fed by Roche-lobe overflow (Bhattacharya & van den Heuvel 1991). The intense stellar wind and other circumstellar matter plays an important role in such systems as the site of scattering and absorption of X-rays from the neutron star.

Extensive X-ray observations of Cen X-3 were carried out over the last 20 years (see for reviews Day & Tennant [1991], Nagase et al. [1992], van der Klis [1993]). Evidence for the presence of material trailing behind the neutron star was provided by X-ray measurements at 2.5–7.5 keV obtained with the *Copernicus* observatory (Tuohy & Cruise 1975). Absorption dips were found after phase ≈ 0.5. *Ariel-5* observations have shown strong absorption between phases 0.5 and 0.75 (Pounds et al. 1975), that was attributed to the existence of an accretion wake (Jackson 1975). Recent observations with the *Ginga* satellite have also shown a stable structure appearing as pre-eclipse dips at phases 0.6–0.9 and 0.65–0.8 , where the X-ray flux above 15 keV is reduced to a quarter of its post-egress value (Nagase et al. 1992).

LMC X-4 exhibits intensity variations over a wide range of time scales. Large X-ray flares are observed about once per day, the X-ray intensity increases by a factor of up to ~ 20 for a duration of ~ 30 minutes (e.g., White 1978; Kelley et al. 1983; Pietsch et al. 1985; Dennerl 1989; Levine et al. 1991). Flare activity does not show any correlation with orbital phase (Skinner et al.

1980). Two very large flares were detected with *Ginga*; the source luminosity sometimes exceeded ~ 5 Eddington luminosities. An analysis of the energy dependence indicates that during flares the spectrum becomes progressively softer. The appearance of the 13.5 s pulsations with an enhanced and very large modulation amplitude clearly indicates that the flare results from an increase in the accretion rate (Levine et al. 1991). An ≈ 30 day period in the optical and X-ray intensity (Lang et al. 1981) is thought to be associated with precession of the accretion disk.

Flare activity, quasi-periodic oscillations, as well as high- and low-intensity states have been found also in SMC X-1 (e.g., Bonnet-Bidaud & van der Klis 1981; Angelini et al. 1991).

At TeV energies these objects are worse studied. Discussions on this subject can be found in reviews by Fegan (1990) and Chadwick et al. (1990).

Evidence for ≥ 0.25 TeV γ-ray emission from Cen X-3 was first reported by the Durham group at phase around 0.8 (Carraminana et al. 1989a), which corresponds to the neutron star in the vicinity of the ascending node. Further measurements by the Durham group (Brazier et al. 1989) and the Potchefstroom group (North et al. 1990) confirmed VHE emission at this phase, while a detailed search by Thornton et al. (1991) covering the phase range 0.7–0.9 did not yield any evidence for the emission. New analysis of data over four years (1986, 1988–1990) performed by North et al. (1991b) has shown a broad sinusoid with maximum at phases 0.52–0.76 (Fig. 4), which coincide with a position of the accretion wake (Jackson 1975).

Detection of LMC X-4 and SMC X-1 at TeV energies has only been reported by the Durham group (Brazier et al. 1990). Pulsed VHE γ-ray emission has been found at phases 0.5 to 0.7 for LMC X-4, and around phases 0.25 and 0.75 for SMC X-1. Neutral emission above 2×10^{17} eV has been recently observed from LMC X-4 at phases 0.1–0.2 and 0.6–0.7 (Meyhandan et al. 1992). The first phase range agrees with detection at 10^{16} eV (Protheroe & Clay 1985; Meyhandan et al. 1992), the last one agrees well with the TeV detection.

2.4 Cygnus X-3

Cygnus X-3 is an enigmatic object and for this reason it has intrigued astrophysicists since its discovery (Vladimirskii et al. 1973). It is probably a close X-ray binary system. Its IR, X-ray and VHE radiation is modulated by a 4.8h period, which is very stable and is normally assumed to be an orbital period. The object has not been seen at optical wavelengths due in part to its location in the galactic plane at a distance of at least 10 kpc from the Sun. For a detailed review the reader is referred to Bonnet-Bidaud & Chardin (1988) and van der Klis (1993), see also discussions in Mitra (1991, 1992).

The nature of the companion star is still unknown. It could be a red dwarf, a white dwarf, or a helium main-sequence star. Recent advances in IR instrumentation have allowed for near-infrared spectroscopy, which shows strong, broad emission lines reminiscent of those of a Wolf-Rayet star (van Kerkwijk et al. 1992). The Wolf-Rayet spectrum of Cyg X-3 probably indicates a strong stellar wind, which is optically thick in the IR, out to distances, larger than the orbital separation. The observed rate of increase of the orbital period of Cyg X-3 allows to estimate the rate of mass loss from the companion, that, in turn, gives an estimation of the companion mass as $\approx 10 M_\odot$.

Fig. 5 shows the evidences for TeV and PeV emission from Cyg X-3 collected by Protheroe (1987). The early observations (pre-1980) indicate VHE γ-ray emission at phases $\approx 0.1 - 0.2$ and 0.7–0.8, all the later observations at TeV energies are clustered around 0.6–0.7. This general agreement in phase of emission is very striking and implies that Cyg X-3 is a powerful emitter of VHE γ-rays.

More recent evidence for TeV emission was found by the Durham Group, which has detected 12.6 ms pulsations (Chadwick et al. 1985a). A periodic signal has been observed in episodes near the phase of X-ray maximum (around phase 0.6) through several years (Bowden et al. 1992b) and has been confirmed by the Adelaide group (Gregory et al. 1990). Such pulsations, however, have not been seen in several other TeV experiments. For a discussion see Chadwick et al. (1990) and Weekes (1992).

2.5 Her X-1

The nature of the X-ray binary system Her X-1 is clear. The companion star has a mass of $\approx 2.2 M_\odot$, placing this system intermediate to high- and low-mass X-ray binaries. The system was also observed in the IR and visible bands and γ-rays. Three periods have been detected in X-rays: a 1.24 s spin period, a 1.7 d orbital period, and ≈ 35 d variations consisting of alternating *high on* and *low on* states of 11 and 5 days duration, respectively, separated by intervals of relatively low X-ray flux (Jones & Forman 1976). The 35 d periodicity is usually treated as resulting from precession of the accretion disk (e.g., Crosa & Boynton 1980), although free precession of the neutron star is also considered (e.g., Bisnovatyi-Kogan et al. 1990). For a discussion of observational features see, e.g., Hutchings et al. (1985), Deeter et al. (1991) and references therein.

Her X-1 is probably the most extensively observed binary source at TeV and PeV energies. The detection of TeV γ-ray emission was first reported by the Durham group (Dowthwaite et al. 1984). The behaviour of Her X-1 at VHE is not yet well understood. Reported episodes of TeV/PeV emission last between a few and 100 minutes. The outbursts do not have a clear correlation with the orbital or 35 day precession periods. Emission occurs at all phases including the phase corresponding to the X-ray eclipse. A detailed discussion on this subject can be found in reviews by Weekes (1988, 1992) and Chadwick et al. (1990).

2.6 4U 0115+63

It is a recurring transient X-ray pulsar with a Be-star companion. Outbursts observed are not related to the orbital phase, but are caused by sudden enhancement of the mass loss of the Be star (Rose et al. 1979). In several cases a period of X-ray activity was found to be preceded by the onset of optical brightening (Kriss et al. 1983).

The detection of TeV γ-rays pulsed at the 3.6 s period was first reported by the Durham group (Chadwick et al. 1985b), although the object may also have been detected earlier (Stepanian et al. 1972). 4U 0115+63 can be regarded as an established, but possibly sporadic VHE γ-ray source (Chadwick et al. 1990; Weekes 1992). There is no evidence for any preferred orbital phase for the emission.

3. Models for VHE Gamma-Ray Production

The VHE γ-ray production in binary systems seems to be clear, apart from the cause of the observed periodicity in the γ-ray flux. The VHE γ-rays (and γ-rays of higher energies) are thought to result from the decay of energetic π^0-mesons produced by the interactions of accelerated protons (or nuclei) with matter or a background radiation. Along with the direct production, π^0-mesons occur also due to decay of various mesons and hyperons. The decay modes and branching ratios of all corresponding reactions are well-known, which allows one to calculate the γ-ray spectrum.

In the astrophysical context, the production of high-energy γ-rays (and neutrinos) in pp-interactions (e.g., Stecker 1970; Levy & Goldsmith 1972; Stephens & Badhwar 1981), and $p\gamma$-interactions (e.g., Stecker 1973, 1979) by relativistic protons has been discussing during more than thirty years.

A target material for accelerated particles could be a companion star (Vestrand & Eichler 1982; Berezinsky et al. 1985; Gaisser & Stanev 1985), X-ray photons around the neutron star (Mastichiadis 1986; Rudak & Meszaros 1991), an accretion disk (Protheroe & Stanev 1987a; Slane & Fry 1989; Cheng et al. 1991, 1992), a gas tail (Hillas 1984), interstellar matter (e.g., Stephens & Badhwar 1981; Berezinsky et al. 1993), or giant molecular clouds (Aharonian 1991). Interactions of cosmic rays with the solar surface have been studied by Moskalenko et al. (1991a), Seckel et al. (1991), and Moskalenko & Karakula (1993a). Kazanas & Ellison (1986) considered π^0-production by relativistic neutrons. The influence of a strong magnetic field was analyzed by Dermer (1990). Various production mechanisms of VHE γ-rays and neutrons, as applied to Cyg X-3, were discussed by Bednarek (1992). For a recent review of γ-ray and neutrino astronomy in general we refer to

Berezinsky et al. (1991).

The efficiency of VHE γ-ray production in the matter surrounding a source of VHE protons has been analyzed in detail by Stenger (1984). It was shown that the maximum efficiency of VHE γ-ray production occurs at a column density of $\approx$ 50 g/cm^2. Under such condition 1 TeV photon emission can be as much as 2.6% of the proton intensity at 1 TeV, for an E^{-2} proton spectrum. Somewhat less efficiency, $\geq$ 0.5 of maximal, occurs in the range $\approx$10–130 g/cm^2. Too few matter will not yield any observable intensity of γ-rays, while too much matter will lead to their total absorption.

The calculation of the efficiency of VHE γ-ray production in $p\gamma$-collisions seems to be much more complicated, because it depends severely on the spectrum of background photons, and their angular distribution, moreover, the VHE γ-rays produced are subject to $\gamma\gamma$-pair attenuation that causes a pair-Compton cascade. For the mental picture, when protons lose all their energy via photopion production in the absence of the pair-Compton cascade the efficiency (Karakula et al. 1994) would be as high as $2K^{\alpha-2}/\alpha$, where K is the inelasticity coefficient, and α is the spectral index of the proton spectrum. This happens in the case of a thin photon field around a particle source when a high magnetic field nearby is capable of trapping protons.

A number of models have been put forward for the explanation of the VHE γ-ray light curves observed from X-ray binaries. The light curve of Cygnus X-3 has attracted the greatest interest. In the following we will concentrate on the main physical scenarios in which the above mechanisms of γ-ray production have been applied.

In an early explanation by Vestrand & Eichler (1982), it was suggested that particles are accelerated near the neutron star and emitted isotropically. At two points in the neutron star orbit, the atmosphere of the companion star acts as a target for the VHE particles (see Fig. 6a). This model accounts for the narrow pre- and post-eclipse pulses, which correspond to the orbital phases $\approx$ 0.15 and $\approx$ 0.85, accordingly. The duty cycle of the pulses and their phase separation are determined by the geometry of the system. Besides, the luminosity of the pulsar in the VHE particles must be much higher than the observed γ-ray luminosity, since only a small fraction of the particles interacting with the companion atmosphere gives rise to the observed γ-ray flux.

Indeed, the early observations (pre-1980) of Cygnus X-3 indicate VHE γ-emission at phases $\approx 0.1-0.2$ and $\approx 0.7-0.8$, but all the later observations have shown the strongest emission at phases $\approx 0.6-0.7$ to be near the phase of the X-ray maximum (Fig. 5). Here the neutron star is assumed to be in front of the companion, which seems to rule out the stellar atmosphere as the target.

A model has been proposed by Hillas (1984) in which a high-energy proton beam falls on the companion star producing a fountain of stellar matter.

In this case, the target material is a gas tail consisting of the lifted matter, and the orbital motion is responsible for the asymmetry (Fig. 6b). Protheroe & Stanev (1987a) suggested another possibility, basing on the accretion disk corona model by White & Holt (1982) developed to explain X-ray light curve of Cyg X-3. Authors find that two bulges in the outer rim of the accretion disk, which are required to fit the observed X-ray light curve, could provide target material for the production of the γ-rays observed at two distinct phases (Fig. 6c). The 4.8h periodicity can be caused by motion of the bulges, which are orbiting the neutron star with the orbital period of the binary system. The observed variability in flux and phase of γ-ray emission, in the model, may be connected with magnetic steering effects.

Magnetic steering of particle trajectories in the magnetic field of the companion was suggested by Gorham & Learned (1986) in order to explain observations of the pulsating TeV γ-ray signal during the nominal 6-h X-ray eclipse of Her X-1 by HZ Her. A similar model, as applied to Vela X-1 and Cen X-3, was considered by Mannings (1992).

All models can be split in two categories, those which suggest γ-ray production far from the neutron star, and others where the VHE γ-rays are assumed to be produced in the vicinity of the neutron star. Models of the first type like that of Vestrand & Eichler (1982) can easily explain the orbital periodicity in γ-ray flux from clear geometrical consideration, but the phase of the emission is difficult to understand and the particle luminosity must be too high to provide the observed γ-ray flux. The second-type models seem to be more attractive from the view point of energy budget, but the correct phase of the γ-emission requires (Protheroe & Stanev 1987a) invoking of a special configuration of the magnetic field, a monoenergetic particle beam etc. The most preferable scenario appears to be one with an accretion wake as a target (a scheme like that of Hillas [1984]). However, as we show in section 4.2, the orbital modulation of the VHE γ-ray flux should probably take place in massive binaries even in the case of originally steady γ-emission (e.g., as in the models of Slane & Fry [1989], Cheng et al. [1991]), while the first-type models could be applicable at UHE. Obviously, in this case the VHE and UHE γ-ray light curves could be essentially different.

4. Propagation of VHE Gamma-Rays

Being produced, VHE γ-rays consequently pass through regions with various physical conditions, which have a strong influence on the observed γ-ray flux. These regions can be separated into

- near a neutron star environment filled with accreting matter, X-ray photons, and a strong magnetic field;
- space in a binary system filled with IR, visible, and UV radiation of a companion star and a gas shell around the system;

– interstellar space contains 2.7 K background photons.

Everywhere the two-photon pair production $\gamma\gamma \to ee$ is likely to absorb a part of VHE photons. Besides, one-photon pair production is possible in a strong magnetic field near the neutron star, together with Compton scattering* and the pair production in accreting gas or the companion star matter in the system.

The kinematics of the reaction of two-photon pair production is well-known. It has a threshold, since the energy of two colliding photons in the center-of-mass system should exceed the rest mass of the electron-positron pair ($2mc^2$). Therefore

$$\varepsilon E_\gamma > 2m^2c^4/(1-\cos\vartheta), \tag{1}$$

where ε and E_γ are the energies of the photon and the γ-quantum respectively, ϑ is the angle between the momenta of the two photons in the observer frame. Taking $\varepsilon = 1$ eV and $\vartheta = 90°$ one can obtain that γ-rays of ≥ 0.5 TeV should be absorbed. There will be no absorption if a source of soft photons lies behind the source of TeV γ-rays, since $\cos\vartheta = 1$ in this case.

The total cross section of the process $\gamma\gamma \to ee$ is known from QED (Jauch & Rohrlich 1980)

$$\sigma_{\gamma\gamma} = \frac{\pi r_e^2}{2}(1-\beta^2)[(3-\beta^4)\ln\left|\frac{1+\beta}{1-\beta}\right| - 2\beta(2-\beta^2)], \tag{2}$$

where $r_e = e^2/mc^2$ is the classical electron radius, $\beta = (1 - m^2c^4/\varepsilon_c^2)^{1/2}$, and ε_c is the photon energy in the center-of-mass system. The cross section, after reaching a peak a little above threshold, decreases roughly as $\varepsilon_c^{-3/2}$.

The optical depth for VHE γ-rays is given by

$$\tau_{\gamma\gamma} = \int\int\int\int \frac{dN(\varepsilon,\mathbf{\Omega},x)}{d\varepsilon d\mathbf{\Omega}}\ \sigma_{\gamma\gamma}(\varepsilon, E_\gamma, \cos\vartheta)(1-\cos\vartheta)\ d\varepsilon d\mathbf{\Omega} dx, \tag{3}$$

where $\frac{dN(\varepsilon,\Omega,x)}{d\varepsilon d\Omega}$ is the differential number density of background photons at the point x, $\mathbf{\Omega}$ is the solid angle, and the integral is taken along the path of the γ-rays.

For an isotropic distribution of background photons, the absorption probability per unit of path length (the inverse mean free path) is

$$\frac{d\tau_{\gamma\gamma}}{dx} = \frac{1}{2}\int\int \sigma_{\gamma\gamma}\frac{dN(\varepsilon)}{d\varepsilon}(1-\cos\vartheta)\sin\vartheta d\vartheta d\varepsilon, \tag{4}$$

and falls with increasing γ-ray energy. If the spectrum of photons is the blackbody type, then the number density of photons per an energy interval

* we do not consider interactions with matter, although photons leave the primary beam that is equivalent to absorption.

is expressed as

$$\frac{dN(\varepsilon)}{d\varepsilon} = n(\varepsilon) = \frac{1}{\pi^2(\hbar c)^3}\frac{\varepsilon^2}{e^{\varepsilon/kT}-1}. \tag{5}$$

However, a mere calculation of the optical depth for the absorption is not sufficient. The absorbed γ-rays will produce electron-positron pairs, which will emit, in turn, γ-rays in inverse Compton scattering or more pairs in collisions with ambient photons, and will cause to a pair-Compton cascade. In this case, one has to solve the transfer equation for photons, taking into account their absorption and re-emission.

While two-photon pair production is a familiar and well-studied process in free space, one-photon pair production is truly exotic, as it probably only occurs in astrophysical sources (see Harding [1991] for a review of processes in strong magnetic fields). A single-photon pair production in the presence of an external magnetic field was first described by Klepikov (1954), but it did not receive much attention until the discovery of pulsars in the late sixties.

The threshold for producing a pair in the ground state is $2mc^2/\sin\theta$, where θ is the angle between the photon momentum and the magnetic field $\mathbf{B}$. Because of the quantum nature of this process, the cross section shows a complex sawtooth structure with a resonance peak at each of the pair state thresholds. An asymptotic expression for the mean free path l of a photon of energy E_γ is (Erber 1966; see also Harding 1991)

$$l = \frac{\lambda_e}{\alpha}\frac{B_{cr}}{B\sin\theta} \times \begin{cases} 5.31\exp(4/3\chi) & \chi \ll 1, \\ 3.33\chi^{1/3} & \chi \gg 1, \end{cases} \tag{6}$$

where

$$\chi = \frac{E_\gamma}{2mc^2}\frac{B\sin\theta}{B_{cr}},$$

λ_e is the electron Compton wavelength, α is the fine structure constant, and $B_{cr} = \frac{m^2c^3}{e\hbar} \approx 4.4\times 10^{13}$ Gs. So the process becomes important for γ-rays of ≈ 1 TeV in magnetic fields above $\approx 4\times 10^6$ Gs.

Let us trace consequently the way of γ-rays from the region of their production to an observer.

4.1 Near the Neutron Star Environment

Two factors at least operate in the vicinity of the neutron star. The X-rays emitted by matter falling onto the neutron star can provide a very effective medium for $\gamma\gamma$-pair absorption of VHE γ-rays. If γ-rays were produced somewhere close to the inner rim of the accretion disk, a strong magnetic field in the immediate neigbourhood of the neutron star surface can provide their conversion into electron-positron pairs. These lead to attenuation of the γ-ray flux in certain energy regions. Let us consider these factors in some detail.

4.1.1 The Accretion Disk Corona

Using Cyg X-3 as an example, the absorption of VHE γ-rays in the radiation field of the accretion disk corona (in a model by White & Holt [1982]) has been considered by Protheroe & Stanev (1987b). In this model, X-rays produced near the neutron star are scattered in a high-temperature optically thick cloud of gas (the corona), which may result from evaporation off the accretion disk due to X-ray heating. This cloud would therefore appear as an extended source. Evidence of such a corona is actually shown by several X-ray binaries (Mason 1989).

The absorption length was calculated, assuming an isotropic radiation field at a spherical region of fully ionized gas of radius $X = 0.7R_{\odot}$, and temperatures 10^7 and 6×10^7 K (Fig. 7). If a modulated component of the IR emission of Cyg X-3, $F = 4$ mJy at 2.2 μm, is due to thermal bremsstrahlung from the corona, then the mean free path of γ-rays would be as small as $\approx X/5$ at 1 TeV.

This calculation can be considered as an example, since the temperature of the gas is unlikely to be too high. Recent instrumental improvements have made possible near-infrared spectroscopy, which shows the presence of lines of relatively low excitation in the IR spectrum (van Kerkwijk et al. 1992). It seems inconsistent with any model for Cyg X-3 that requires a very high temperature ($\geq 10^6$ K) in the IR-producing region such as an accretion disk corona model.

4.1.2 The Radiation Field of the Accretion Disk

The radiation field of an accretion disk is essentially anisotropic and calculation of the attenuation effect is more interesting as well as more complicated. An effect of such field on VHE γ-ray flux has been studied by Carraminana (1992) and Bednarek (1993).

Both models used include the following assumptions. In the standard picture, accretion disks are formed by thin concentric circles emitting in thermal equilibrium (Pringle 1981). The temperature T at any point of the disk is dependent only on the circle radius R,

$$T = T_{max}(R/R_{ns})^{-3/4}, \tag{7}$$

where $R_{ns} \approx 10^6$ cm is the radius of the neutron star. T_{max} is the characteristic blackbody temperature of the disk determined by the accretion rate $\dot{M}$ as

$$T_{max} = \left(\frac{3G\dot{M}M}{8\pi\sigma_{sb}R_{ns}^3}\right)^{1/4} \approx 1.234\,\mathrm{keV}\left(\frac{L_x}{10^{37}\ \mathrm{erg/s}}\right)^{1/4}\left(\frac{R_{ns}}{10^6\ \mathrm{cm}}\right)^{-1/2}, \tag{8}$$

where $L_x = GM\dot{M}/2R_{ns}$ is the luminosity of the disk and σ_{sb} is the Stefan-Boltzmann constant. Photons emitted by a disk range from medium hardness X-rays at the centre of the disk to infrared at the edge.

The models include VHE γ-ray production at the co-rotation radius (Carraminana 1992), R_{co}, defined as the radius where the Keplerian rotation of the disk equals the spin rate of the star,

$$R_{co} = \left(\frac{GMP_{rot}^2}{4\pi^2}\right)^{1/3} = 1.69 \times 10^8 \text{ cm } \left(\frac{M}{1.44 M_\odot}\right)^{1/3} \left(\frac{P_{rot}}{1 \text{ s}}\right)^{2/3}, \quad (9)$$

here P_{rot} is its spin period, *or* at a radius R_γ that is a free parameter $R_{in} \leq R_\gamma \leq R_{out} = 3 \times 10^9$ cm (Bednarek 1993), whereas the inner radius of the disk, R_{in}, was chosen close to the Alfven radius

$$r_A \cong 3 \times 10^8 \text{ cm } \left(\frac{L_x}{10^{37} \text{ erg/s}}\right)^{-2/7} \left(\frac{B_s}{10^{12} \text{ Gs}}\right)^{4/7} \left(\frac{R_{ns}}{10^6 \text{ cm}}\right)^{10/7}, \quad (10)$$

where B_s is the surface magnetic field strength.

The optical depth could be obtained from eq. (3) by integrating along the γ-ray path. In order to simplify calculations, photons from the disk are assumed to be emitted only at right angles to the disk plane (Carraminana 1992). Therefore, if VHE γ-rays are emitted radially towards an observer, the inclination angle i of the orbital plane corresponds to the angle between high energy γ-rays and photons from the disk.

Although the model for the radiation field of the accretion disk considered by Bednarek (1993) is different, because it includes the isotropic emission of photons by each surface element of the disk, the results obtained for the three binary systems (Vela X-1, Her X-1, and Cen X-3) are similar to those of Carraminana (1992).

The model was applied to the following binary systems, reported as TeV sources: Vela X-1, 4U 0115+63, Cen X-3, Her X-1, Sco X-1, Cyg X-3. The X-ray luminosities L_x, inclination angles i, and rotation periods P_{rot}, which are close to those used for the calculations, are listed in Tables II and III. The compact object was implicitly assumed to be a neutron star ($M = 1.44 M_\odot$ and $R_{ns} = 10^6$ cm).

Figure 8 shows the transmission of γ-rays, $\exp(-\tau_{\gamma\gamma})$, as a function of their energy in the system considered. These can be grouped as follows:

Vela X-1 is transparent to high energy photons and no effect on its high energy spectrum is predicted.

4U 0115+63, Cen X-3 and Her X-1 show a dip in the GeV–TeV region of their spectra. The transmission is low for E_γ between ~ 10 GeV and ~ 1 TeV for the Cen X-3 and Her X-1 systems. A slow increase begins at $E_\gamma \sim 1$ TeV.

The two systems, Sco X-1 ($i = 30°$) and Cyg X-3, show total absorption in large regions of their spectra. It is clear that absorption is severe and γ-rays cannot be emitted from the co-rotation radius that is too close to the neutron star.

Fig. 6 shows examples, Her X-1, and 4U 0115+63, of how spectra resulting from pair absorption can appear. Taking an input power law with a slope of 2.5, the effects of the absorption and a pair-Compton cascade are shown.

4.1.3 Effect of the Magnetic Field

In most cases the effect of one-photon pair production reaction is small or negligible at TeV energies (e.g., see Bednarek 1993). If a dipolar structure of the magnetic field is assumed, $B(R) = B_s R_{ns}^3/R^3$, then one can estimate from eq.(6) $1/\chi \geq 58.6 - \frac{9}{4}\ln R$, where $B_s = 10^{12}$ Gs is the surface magnetic field strength, $R_{ns} = 10^6$ cm, and where we took $l \geq 10^{10}$ cm as comparable to the accretion disk size. Taking R equal to the Alfven radius $r_A = 3 \times 10^8$ cm (eq.[10]), we obtain $\chi \leq 1/15$. It defines the γ-ray energy region where the effect is negligible as $E_\gamma(\mathrm{eV}) \leq 3 \times 10^{18}/[B(\mathrm{Gs})\sin\theta]$. For the upper limit of the effect, again R equals r_A, $B(r_A) \approx 3.7 \times 10^4$ Gs, that gives $E_\gamma(\mathrm{eV}) \leq 10^{14}/\sin\theta$. Moreover, the real effect should be even less, since the ultrarelativistic proton is initially moving along $\mathbf{B}$, and VHE γ-rays produced by π^0 decay should be first emitted almost parallel to $\mathbf{B}$.

4.1.4 Discussion

Although models considered in this subsection are rather rough since, for instance, the strength of the surface magnetic field of the neutron stars is not precisely known, the X-ray luminosity of the disk may be significantly influenced by the inclination angle of the disk as well as by the X-ray emission from the vicinity and surface of the neutron star, the calculations show the order of magnitude of the effect and the energy regions where one can expect marked attenuation.

Obviously, VHE γ-rays, if observed, have to be produced at sufficiently large distances from the neutron star so that γ-rays can escape without pair creation in the magnetic field and radiation field of the infalling matter. They can neither be produced far away from the neutron star, which is implied by the detection of pulsed TeV signals from several binaries like Vela X-1, Cen X-3, and Her X-1 (Chadwick et al. 1990). On the other hand, VHE γ-rays absorbed in this way would produce a pair-Compton cascade which is able to fill partially the absorption dip in the VHE γ-ray spectrum, although such a cascade in a strong magnetic field will significantly differ from that in free space. Another possibility is photopion production on these same photons. The VHE γ-ray photon producing by proton could escape freely passing through a region with background photons of lower energy and density as the radiation field is essentially anisotropic. Besides, the photopion production reaction is more effective from the viewpoint of energy conversion.

4.2 Propagation at the Binary System

The space around a binary system is filled with IR, visible, and UV radiation of the companion star and the gas shell around the system. The uniform and isotropic photon field of a gas shell, if it exists, leads to some attenuation and a weak orbital modulation of the observed flux of γ-rays, while the approximately radial photon field of a companion star leads to a significant modulation effect and could possibly be the principal cause of the observed γ-ray periodicity connected with orbital motion.

4.2.1 Absorption Due to the Cocoon Photons

The absorption of high-energy γ-rays from Cyg X-3 in its own IR photon field was considered by Apparao (1984) and Protheroe & Stanev (1987b). The IR emission of Cyg X-3 is variable. The 4.8 hr periodicity is not always detectable, although a DC and a modulated component can be usually separated. The IR spectra of Cyg X-3 indicate presence of a strong stellar wind, which is optically thick in the IR, up to well outside the system (van Kerkwijk et al. 1992).

The cocoon model was first proposed by Milgrom (1976) and Milgrom & Pines (1978) to account for the similar shape of the IR and X-ray modulation of Cyg X-3. The central X-ray spectrum is degraded by absorption and scattering through a hot ($T \approx 10^5$ K) and thick (1 g/cm^2) spherical gas shell at a distance, $R_0 \approx 10^{12}$ cm, large compared to the orbital separation. The X-rays heat the cocoon, which emits in the IR by bremsstrahlung.

Assuming that the DC component (the flux $F \sim 10$ mJy at 2.2 μm) is thermal in origin and is due to heating of diffuse matter of typical dimensions $2R_0$ surrounding or nearby the Cyg X-3 system, its temperature could be estimated (Protheroe & Stanev 1987b)

$$T \geq 10^6 \text{ K} \, \frac{F(2.2\ \mu\text{m})}{10 \text{ mJy}} \left(\frac{R_0}{R_\odot}\right)^{-2} \left(\frac{D}{10 \text{ kpc}}\right)^2, \tag{11}$$

where D is the distance to Cyg X-3.

Using $R \geq 11 R_\odot$ gives the effective temperature $T \leq 10^4$ K. No significant absorption in TeV γ-rays will be seen under such conditions. If the emitting region would be confined to the dimensions of the binary system, which is estimated to be about 10^{11} cm, the optical depth would reach of a few 1.

4.2.2 The Orbital Modulation

The effect of the companion star radiation on the shape of the light curve of Cyg X-3 in the TeV region was first noticed by Protheroe & Stanev (1987b). The absorption expected as a function of the orbital phase has been calculated. It was assumed that high-energy protons are produced near the neutron star and interact in target material to produce γ-rays. Those γ-rays that are travelling in a cone around the orbital axis with an half-angle equal to the inclination of the system (assumed to be 60°) may be observable at Earth. A $3.95M_\odot$ helium companion star, a $1.4M_\odot$ neutron star, the $\sim 2.5R_\odot$ binary separation, and a circular orbit have been assumed. The optical depth calculated at orbital phases $\varphi \approx 0.25$ and 0.63, taking into account the helium star temperature $5 \times 10^4 - 10^5$ K, was found to be too high, while the observation of TeV γ-rays at the phases (Fig. 5) implies that the optical depth is unlikely to be much in excess of one at these phases.

A more detailed analysis, taking into consideration the orbital ellipticity was independently performed by Moskalenko et al. (1991b, 1993a,b). It was first applied to the Cyg X-3 system, and then to other close binaries detected as TeV sources (Moskalenko & Karakula 1994).

The main simplifying assumption in this model is that photons emitted by the companion star travel radially outwards from its surface. It was chosen because of the following reasons:

- it is correctly gives the number density of soft photons;
- for distances large enough, it is a close approximation. For regions closer to the star, the surface element of the star nearest to the VHE photon is the one contributing the most to the local flux. The absorption probability calculated is close to the exact one even in the vicinity of the companion star;
- the practical reason is that calculations are essentially simplified.

The number density of the soft photons from a companion star per energy interval at any point $(d, \cos\alpha)$ is approximated by

$$\frac{dN}{d\varepsilon}(\varepsilon, \cos\vartheta) = \left(\frac{R_c}{d}\right)^2 \frac{n(\varepsilon)}{2}\delta(\cos\vartheta - \cos\alpha), \tag{12}$$

where the Z-axis is directed to the observer (see Fig. 10), d is the distance from the star, α is the polar angle, ϑ is the angle between the Z-axis and the direction of a photon, δ is the Dirac function, $n(\varepsilon)$ is the energy distribution of black-body photons (eq. [5]) at the companion's surface, and R_c is the effective radius of a companion star at which the number density of photons is equal to the Planck density.

The flux of VHE gamma-rays at the observer's position I_{obs} would be

$$I_{obs}(E_\gamma) = I_0(E_\gamma) exp(-\tau_{\gamma\gamma}(E_\gamma)), \tag{13}$$

where $I_0(E_\gamma)$ is the original flux of γ-rays of energy E_γ escaping from the region of their production. The optical depth is given by an integral $\tau_{\gamma\gamma}(E_\gamma) = \int d\ell \frac{d\tau_{\gamma\gamma}}{dx}$ (eq. [4]), which is taken along the line of sight from near the source region to an observer. Here the inverse mean free path of Z-directed γ-rays at the point $(d, \cos\alpha)$ is given by

$$\frac{d\tau_{\gamma\gamma}}{dx}(E_\gamma) = \frac{4R_c^2}{E_\gamma^2 d^2}\int_{mc^2}^{\infty} d\varepsilon_c\, \sigma_{\gamma\gamma}(\varepsilon_c)\varepsilon_c^3 \int_{\varepsilon_c^2/E_\gamma}^{\infty} d\varepsilon\, \frac{n(\varepsilon)}{\varepsilon^2}\delta(1-\frac{2\varepsilon_c^2}{\varepsilon E_\gamma}-\cos\alpha). \quad (14)$$

If a neutron star orbit is elliptical, the orbital phase corresponding to an angular position ψ is calculated as

$$\varphi = \frac{1}{2\pi ab}\int_0^{\psi} d\psi' r^2(\psi'), \quad (15)$$

where a is the semi-major axis of the orbit, $b = a(1-e)$ is the semi-minor axis, e is the eccentricity, $r(\psi) = \frac{a(1-e^2)}{1-e\sin(\psi-\omega)}$ is the distance from the neutron star to a companion star, ω is the longitude of periastron (Figure 10 shows the negative direction of the ω-angles), and the choice $\psi = 0$ corresponds to the neutron star lying behind the companion.

Fig. 11 shows the calculated phase of the VHE radiation versus eccentricity for some longitudes of periastron ω and for an inclination angle $i \approx 90°$. The phase of the radiation assumed corresponds to the position of the neutron star in front of the companion. The largest or smallest phase of the γ-ray maximum is reached when the major axis of the orbit makes a right angle to the line of sight ($\omega \approx 0$ or $180°$). Obviously, the exact phase of the maximum, which can differ from the calculated one, depending on the distribution of matter around the neutron star and geometry of a particle beam.

In Fig. 12 the optical depth is shown as a function of $\sin i \times \cos\psi$ for γ-rays of 0.1, 1, 10 and 100 TeV. The calculations were carried out for a circular orbit and two temperatures of a black-body photon field, $kT = 3$ eV and 4 eV. The other parameters are $R_c = 1\times 10^{12}$ cm and $a = 2\times 10^{12}$ cm. As illustrated, there is no absorption, $\tau_{\gamma\gamma}(E_\gamma) = 0$, only for the case $\sin i \times \cos\psi = -1$, i.e., where the observer is in the orbital plane ($i = 90°$) and the neutron star lies between the companion and the observer ($\psi = 180°$). In the other positions of the neutron star a pair-Compton cascade will more or less effectively develop in an anisotropic radiation field of the companion.

The attenuation effect in close massive binaries is more pronounced in the TeV energy range. A near black-body spectrum of OB supergiants has an effective temperature of some 3-4 eV (Allen 1973), that corresponds to the absorption maximum at 1-10 TeV as the cross section of pair production $\gamma\gamma \to ee$ has a sharp maximum near the threshold. Thus, the TeV γ-rays should only be observed if their source lies between the companion star and an observer. In such a system VHE γ-rays are most probably produced near the neutron star.

The model described, has been applied (Moskalenko & Karakula 1994) to the well-known close binary systems, Vela X-1, Cen X-3, SMC X-1, LMC X-4, GX 301-2, 4U 0115+63, 4U 1538-52, Her X-1, and Cyg X-3. Most of them were reported as sources of TeV and/or PeV radiation and are sketched in Fig. 1 (see also section 2). Light curves (I_{obs}/I_0, eq.[13]) for γ-rays of 0.1, 1, 10 and 100 TeV were calculated (Fig. 13) under the assumption that the neutron star emits γ-rays at a steady level. The curves are given for the parameter values, listed in Table II. For each system the maximum of the light curve occurs at the same phase for various energies, but the form of light curves is different. This effect results from the energy dependence of the optical depth (see Fig. 12).

The systems with about circular orbits, Cen X-3, 4U 1538-52, SMC X-1, LMC X-4, and Her X-1, show near symmetrical shape of the light curves, while the other systems indicate noticeable asymmetry.

Light curves of two systems, Her X-1, and 4U 0115+63, have broad maxima. This is due to the fact that the companion star is relatively cold (8 000 K) as in Her X-1, or the binary separation in 4U 0115+63 is too large in comparison with the companion star radius. A weak orbital modulation in the two last cases allows one to observe VHE γ-rays at almost arbitrary phase if there are conditions to produce them, i.e., a particle beam and a suitable target. Actually, VHE γ-ray emission from both systems is always episodic and comes at random orbital phases (see sections 2.5 and 2.6). In the case of the other binaries, the model does well restrict the phase regions where such emission could be observed.

Vela X-1 and Cen X-3 are examples of systems, where VHE radiation is coming at "forbidden" orbital phases. The orbital modulation of VHE emission from Vela X-1 was found to be very weak (see Fig. 3 and section 2.2). The reason for the VHE γ-radiation being emitted at "forbidden" phases remains a puzzle, although there is definitely some concentration of positive detections at the "right" phases.

The VHE γ-ray flux of $\geq$0.25 TeV at phase 0.7-0.8 has first been reported from Cen X-3 (Chadwick et al. 1990; North et al. 1989). This phase corresponds to the neutron star in the vicinity of the ascending node. In the context of the model, the appearance of TeV radiation is difficult to understand in such a phase range. Even if the γ-rays have been produced near the neutron star, the attenuated flux from Cen X-3 at phase 0.75 is a negligible fraction of the original one, about 4.33×10^{-11}, 6.1×10^{-12}, 1.87×10^{-3} and 0.35 for E_γ= 0.1, 1, 10 and 100 TeV respectively. Recent re-analysis by North et al. (1991b) has shown the VHE γ-ray maximum to be located at the phase $\approx 0.52 - 0.76$ (Fig. 4), while a detailed search by Thornton et al. (1991) covering the phase range 0.7-0.9 has not found any significant evidence for the emission. These two results do not contradict the notion that the gamma-ray maximum should be observed at phases of about 0.5

(Fig. 13).

Systems Cyg X-3 and GX 301-2 show very similar light curves, the maxima are essentially shifted. This is due to the fact that their orbits are the most eccentric and have very similar orientations.

Cyg X-3 is probably an example of a system with fast apsidal motion $P_{aps} \geq 30 - 60$ yr (Ghosh et al. 1981; van der Klis 1990). In this case, the transition of the phase of VHE emission from ≈ 0.8 to ≈ 0.6, observed at the beginning of the 1980s (Fig. 5), may be connected with apsidal motion in the system (Moskalenko et al. 1993b). If so, the eccentricity should be ≥ 0.4 (see Fig. 11), which agrees with other calculations (Ghosh et al. 1981; Giler 1989). Observation of the second maximum at phase ≈ 0.2 is difficult to understand in the framework of the model.

4.3 Interstellar Propagation

The Galaxy is almost transparent to high-energy γ-rays. The main absorption process is two-photon pair production, since even in the galactic plane the interstellar medium constitutes a column density much less than one radiation length. The importance of the 2.7 K blackbody photons from the viewpoint of attenuation of γ-rays via pair production was first discussed by Jelley (1966) and Gould & Schreder (1966, 1967). The absorption probability of high-energy radiation from a galactic source, Cyg X-3, by this process was calculated by Gould (1983).

The mean free path is shown as a function of γ-ray energy in Figure 14. The process is most important for γ-rays above 10^{14} eV. The minimum path length is as small as ~ 7 kpc at $\sim 10^{15}$ eV. Such attenuation is negligible for the TeV region.

5. Conclusions

As we can see, by virtue of absorption processes, the flux and phase of VHE radiation depend strongly on the site of its production and the physical conditions in the system, while the interstellar attenuation is negligible. One more task is obvious now. It is to search for absorption features and other irregularities in the VHE γ-ray spectra. They are expected to be observable in relatively narrow energy bands and their detection would throw light upon the origin of VHE γ-rays in binary systems. Otherwise, it would seem very unnatural if the γ-ray spectrum from a source could be described with a simple power law. Certainly, the process of pair-Compton cascade would somewhat smooth out this otherwise fairly clear picture.

The TeV region seems to be most important from the viewpoint of studying emission processes and particle acceleration in the sources. And, although the problem of data reliability remains a source of headache for γ-ray telescope teams (since the γ-ray emission is always episodic and comes in at random phases), the TeV region is the energy region for which the new Cherenkov technique, with improved sensivity and the possibility of an accurate timing analysis, have already been developed. We may also note some advance in the theory, in spite of that we can not predict *a priori* what and when we are expected to see in the VHE region yet. We are, however, already able to identify the energy regions and phases where such VHE radiation could *unlikely* appear. Clearly, large progress has been made in this field!

With the discovery of VHE γ-rays from cosmic sources, a new era has actually started in astrophysics and particle physics. The study of this phenomenon requires common efforts of traditional observational astronomers, who study stellar evolution and mass transfer processes, specialists in X-ray optics, who develop new satellite telescopes, and the experience of particle physicists, who are working with ground-based millisecond techniques. Growing interest in the study of X-ray binary systems and technological progress has made available excellent spectroscopic information over a vast energy range, from radio and IR to X-rays, as well as accurate methods for timing analysis in VHE γ-rays. All these provide the assurance that now we can check our notions appeared at earlier stages of γ-astronomy and it gives us hope for further exciting discoveries in this field.

Acknowledgements

I would like to thank Professor Cornelis de Jager for his helpful comments. I am very grateful also to Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste, where part of this work was performed.

References

Aharonian, F. A.: 1991, *ApSS* **180**, 305
Allen, C. W.: 1973, *Astrophysical quantities*, Athlone:London
Angelini, L., Stella, L., and White, N. E.: 1991, *ApJ* **371**, 332
Apparao, K. M. V.: 1984, *ApJ* **287**, 338
Aslanov, A. A., Kolosov, D. E., Lipunova, H. A., Khruzina, T. S., and Cherepashchuk, A. M.: 1989, Cherepashchuk, A. M., ed., *Catalogue of Close Binaries in Late Evolutionary Stages*, Moscow University Press: Moscow [in Russian]
Bednarek, W.: 1992, *AAp* **264**, 331
Bednarek, W.: 1993, *AAp* **278**, 307
Berezinsky, V. S., Castagnoli, C., and Galeotti, P.: 1985, *Nuovo Cimento* **8C**, 185
Berezinsky, V. S., Bulanov, S. V., Dogiel, V. A., Ginzburg, V. L., and Ptuskin, V. S.: 1991, *Astrophysics of Cosmic Rays*, Elsevier: Amsterdam
Berezinsky, V. S., Gaisser, T. K., Halzen, F., and Stanev, T.: 1993, *Astroparticle Physics* **1**, 281
Bhattacharya, D, and van den Heuvel, E. P. J.: 1991, *Physics Reports* **203**, 1
Bisnovatyi-Kogan, G. S., Mersov, G. A., and Sheffer, E. K.: 1990, *Soviet Astr.* **34**, 44
Blondin, J. M., Kallman, T. R., Fryxell, B. A., and Taam, R. E.: 1990, *ApJ* **356**, 591

Bonnet-Bidaud, J. M., and van der Klis, M.: 1981, *AAp* **97**, 134
Bonnet-Bidaud, J. M., and Chardin, G.: 1988, *Physics Reports* **170**, 325
Bowden, C. C. G., Bradbury, S. M., Chadwick, P. M., Dickinson, J. E., Dipper, N. A., Edwards, P. J., Lincoln, E. W., McComb, T. J. L., Orford, K. J., Rayner, S. M., and Turver, K. E.: 1992a, *J. Phys. G: Nucl. Part. Phys.* **18**, L127
Bowden, C. C. G., Bradbury, S. M., Brazier, K. T. S., Carraminana, A., Chadwick, P. M., Dipper, N. A., Edwards, P. J., Lincoln, E. W., Mannings, V. G., McComb, T. J. L., Orford, D. J., Orford, K. J., Rayner, S. M., and Turver, K. E.: 1992b, *J. Phys. G: Nucl. Part. Phys.* **18**, 413
Bowden, C. C. G., Bradbury, S. M., Chadwick, P. M., Dickinson, J. E., Dipper, N. A., McComb, T. J. L., Orford, K. J., Rayner, S. M., and Turver, K. E.: 1993, *Proc. 23rd Intern. Cosmic Ray Conf. (Calgary)* **1**, 298
Bradt, H. V. D., and McClintock, J. E.: 1983, *ARAA* **21**, 13
Brazier, K. T. S., Carraminana, A., Chadwick, P. M., Dipper, N. A., Lincoln, E. W., Mannings, V. G., McComb, T. J. L., Orford, K. J., Rayner, S. M., Turver, K. E., and Williams, D. G.: 1989, in Hunt, J., and Battrick, B., eds., *Proc. 23rd ESLAB Symp. on Two Topics in X-Ray Astronomy (Bologna)*, ESA SP-296, **1**, 311
Brazier, K. T. S., Carraminana, A., Chadwick, P. M., Dipper, N. A., Lincoln, E. W., Mannings, V. G., McComb, T. J. L., Orford, K. J., Rayner, S. M., and Turver, K. E.: 1990, *Proc. 21st Intern. Cosmic Ray Conf. (Adelaide)* **2**, 300
Carraminana, A.: 1992, *AAp* **264**, 127
Carraminana, A., Chadwick, P. M., Dipper, N. A., Lincoln, E. W., Mannings, V. G., McComb, T. J. L., Orford, K. J., Rayner, S. M., Turver, K. E., and Williams, D. G.: 1989a, in Ögelman, H., and van den Heuvel, E. P. J., eds., *Timing Neutron Stars*, Reidel: Dordrecht, 369
Carraminana, A., Chadwick, P. M., Dipper, N. A., Lincoln, E. W., Mannings, V. G., McComb, T. J. L., Orford, K. J., Rayner, S. M., and Turver, K. E.: 1989b, *ApJ* **346**, 967
Chadwick, P. M., Dipper, N. A., Dowthwaite, J. C., Gibson, A. I., Harrison, A. B., Kirkman, I. W., Lotts, A. P., Macrae, J. H., McComb, T. J. L., Orford, K. J., Turver, K. E., and Walmsley, M.: 1985a, *Nature* **318**, 642
Chadwick, P. M., Dipper, N. A., Dowthwaite, J. C., Gibson, A. I., Harrison, A. B., Kirkman, I. W., Lotts, A. P., Macrae, J. H., McComb, T. J. L., Orford, K. J., Turver, K. E., and Walmsley, M.: 1985b, *AAp* **151**, L1
Chadwick, P. M., McComb, T. J. L., and Turver, K. E.: 1990, *J. Phys. G: Nucl. Part. Phys.* **16**, 1773
Chanmugam, G., and Brecher, K.: 1985, *Nature* **313**, 767
Cheng, K. S., and Ruderman, M.: 1989, *ApJ* **337**, L77
Cheng, K. S., and Ruderman, M.: 1991, *ApJ* **373**, 187
Cheng, K. S., Yu, K. N., Cheung, T., and Lau, M. M.: 1991, *ApJ* **379**, 290
Cheng, K. S., Cheung, T., Lau, M. M., and Ng, K. W.: 1992, *J. Phys. G: Nucl. Part. Phys.* **18**, 725
Crosa, L. M., and Boynton, P. E.: 1980, *ApJ* **235**, 999
Day, C. S. R., and Tennant, A. F.: 1991, *MNRAS* **251**, 76
Deeter, J. E., Boynton, P. E., and Pravdo, S. H.: 1981, *ApJ* **247**, 1003
Deeter, J. E., Boynton, P. E., Lamb, F. K., and Zylstra, G.: 1987, *ApJ* **314**, 634
Deeter, J. E., Boynton, P. E., Miyamoto, S., Kitamoto, S., Nagase, F., and Kawai, N.: 1991, *ApJ* **383**, 324
Dennerl, K.: 1989, in Hunt, J., and Battrick, B., eds., *Proc. 23rd ESLAB Symp. on Two Topics in X-Ray Astronomy (Bologna)*, ESA SP-296, **1**, 39
Dermer, C. D.: 1990, *ApJ* **360**, 197
Dowthwaite, J. C., Harrison, A. B. Kirkman, I. W., Macrae, J. H., Orford, K. J., Turver, K. E., and Walmsley, M.: 1984, *Nature* **309**, 691
Eichler, D., and Vestrand, W. T.: 1985, *Nature* **318**, 345
Erber, T.: 1966, *Reviews of Modern Physics* **38**, 626

Fazio, G. G., Helmken, H. J., O'Mongain, E., and Weekes, T. C.: 1972, *ApJ* **175**, L117
Fegan, D. J.: 1990, *Proc. 21st Intern. Cosmic Ray Conf. (Adelaide)* **11**, 23
Gaisser, T. K., and Stanev, T.: 1985, *Physical Review Letters* **54**, 2265
Giler M.: 1989, in Stepanian, A. A., Fegan, D. J. and Cawley, M. F., eds., *Proc. Intern. Workshop on VHE Gamma-Ray Astron. (Crimea)*, 91
Ghosh, P., Elsner, R. F., Weisskopf, M. C., and Sutherland, P. G.: 1981, *ApJ* **251**, 230
Gorham, P. W., and Learned, J. G.: 1986, *Nature* **323**, 422
Gould, R. J.: 1983, *ApJ* **274**, L23
Gould, R. J., and Schreder, G. P.: 1966, *Physical Review Letters* **16**, 252
Gould, R. J., and Schreder, G. P.: 1967, *Physical Review* **155**, 1404
Gregory, A. G., Patterson, J. R., Roberts, M. D., Smith, N. I., and Thornton, G. J.: 1990, *AAp* **237**, L5
Haberl, F.: 1991a, *AAp* **252**, 272
Haberl, F.: 1991b, *ApJ* **376**, 245
Haberl, F., and White, N. E.: 1990, *ApJ* **361**, 225
Harding, A. K.: 1991, *Physics Reports* **206**, 327
Hillas, A. M.: 1984, *Nature* **312**, 50
Hillas, A. M.: 1987, in Turver, K. E., eds., *Very High Energy Gamma Ray Astronomy*, Reidel: Dordrecht
Hunt, J., and Battrick, B., eds.: 1989, *Proc. 23rd ESLAB Symp. on Two Topics in X-Ray Astronomy (Bologna)*, ESA SP-296
Hutchings, J. B., Gibson, E. M., Crampton, D., and Fisher, W. A.: 1985, *ApJ* **292**, 670
Jackson, J. C.: 1975, *MNRAS* **172**, 483
Jauch, J. M., and Rohrlich, F.: 1980, *Theory of Photons and Electrons*, Springer: New York
Jelley, J. V.: 1966, *Physical Review Letters* **16**, 479
Jones, C., and Forman, W.: 1976, *ApJ* **209**, L131
Joss, P. C., and Rappaport, S. A.: 1984, *ARAA* **22**, 537
Karakula, S., Kociolek, G., Moskalenko, I. V., and Tkaczyk, W.: 1994, *ApJ Suppl.* **92**, in press
Kazanas, D., and Ellison, D. C.: 1986, *Nature* **319**, 380
Kelley, R., Rappaport, S., and Petre, R.: 1980, *ApJ* **238**, 699
Kelley, R. L., Rappaport, S., Clark, G. W., and Petro, L. D.: 1983a, *ApJ* **268**, 790
Kelley, R. L., Jernigan, J. G., Levine, A., Petro, L. D., and Rappaport, S.: 1983b, *ApJ* **264**, 568
van Kerkwijk, M. H., Charles, P. A., Geballe, T. R., King, D. L., Miley, G. K., Molnar, L. A., van den Heuvel, E. P. J., van der Klis, M., and van Paradijs, J.: 1992, *Nature* **355**, 703
Kiraly, P., and Meszaros, P.: 1988, *ApJ* **333**, 719
Klepikov, N. P.: 1954, *Zh. Eksp. Teor. Fiz.* **26**, 19
van der Klis, M.: 1989, *ARAA* **27**, 517
van der Klis, M.: 1990, *Nuclear Physics B (Proc. Suppl.)* **14B**, 107
van der Klis, M.: 1993, *SSR* **62**, 173
Kriss, G. A., Cominsky, L. R., Remillard, R. A., Williams, G., and Stothers, R.: 1983, *ApJ* **266**, 806
Lang, F. L., et al.: 1981, *ApJ* **246**, L21
Levy, D. J., and Goldsmith, D. W.: 1972, *ApJ* **177**, 643
Levine, A., Rappaport, S., Putney, A., Corbet, R., and Nagase, F.: 1991, *ApJ* **381**, 101
Levine, A., Rappaport, S., Deeter, J. E., Boynton, P. E., and Nagase, F.: 1993, *ApJ* **410**, 328
Lewin, W. H. G., van Paradijs, J., and van den Heuvel, E. P. J., eds.: 1993, *X-ray Binaries*, Cambridge University Press: Cambridge
Lewis, W., Rappaport, S., Levine, A., and Nagase, F.: 1992, *ApJ* **389**, 665
Makishima, K., Koyama K., Hayakawa, S., and Nagase F.: 1987, *ApJ* **314**, 619
Mannings, V.: 1992, *AAp* **258**, 335

Mason, K. O.: 1989, in Hunt, J., and Battrick, B., eds., *Proc. 23rd ESLAB Symp. on Two Topics in X-Ray Astronomy (Bologna)*, ESA SP-296, **1**, 113
Mastichiadis, A.: 1986, *AAp* **169**, 373
Meyhandan, R., Dawson, B. R., Clay, R. W., Horton, L., Ulrichs, J., and Winn, M. M.: 1992, *ApJ* **391**, 236
Milgrom, M.: 1976, *AAp* **51**, 215
Milgrom, M., and Pines, D.: 1978, *ApJ* **220**, 272
Mitra, A.: 1991, *ApJ* **370**, 345
Mitra, A.: 1992, *ApJ* **384**, 255
Moskalenko, I. V., and Karakula, S.: 1993, *J. Phys. G: Nucl. Part. Phys.* **19**, 1399
Moskalenko, I. V., and Karakula, S.: 1994, *ApJ Suppl.* **92**, in press
Moskalenko, I. V., Karakula, S., and Tkaczyk, W.: 1991a, *AAp* **248**, L5
Moskalenko, I. V., Karakula, S., and Tkaczyk, W.: 1991b, *Proc. 22nd Intern. Cosmic Ray Conf. (Dublin)* **1**, 544
Moskalenko, I. V., Karakula, S., and Tkaczyk, W.: 1993a, *AApS* **97**, 269
Moskalenko, I. V., Karakula, S., and Tkaczyk, W.: 1993b, *MNRAS* **260**, 681
Nagase, F.: 1989, *Publ. Astron. Soc. Japan* **41**, 1
Nagase, F., Corbet, R. H. D., Day, C. S. R., Inoue, H., Takeshima, T., Yoshida, K., and Mihara, T.: 1992, *ApJ* **396**, 147
North, A. R., Brink, C., Cheng, K. S., de Jager, O. C., Nel, H. I., and Raubenheimer, B. C.: 1989, in Hunt, J., and Battrick, B., eds., *Proc. 23rd ESLAB Symp. on Two Topics in X-Ray Astronomy (Bologna)*, ESA SP-296, **1**, 563
North, A. R., Brink, C., Cheng, K. S., de Jager, O. C., Nel, H. I., and Raubenheimer, B. C.: 1990, *Proc. 21st Intern. Cosmic Ray Conf. (Adelaide)* **2**, 275
North, A. R., Raubenheimer, B. C., Brink, C., de Jager, O. C., Meintjes, P. J., Nel, H. I., van Urk, G., and Visser, B.: 1991a, *Proc. 22nd Intern. Cosmic Ray Conf. (Dublin)* **1**, 328
North, A. R., Raubenheimer, B. C., Brink, C., de Jager, O. C., Meintjes, P. J., Nel, H. I., van Urk, G., and Visser, B.: 1991b, *Proc. 22nd Intern. Cosmic Ray Conf. (Dublin)* **1**, 340
Parkes, G. E., Mason, K. O., Murdin, P. G., and Gulhane, J. L.: 1980, *MNRAS* **191**, 547
Pietsch, W., Pakull, M., Voges, W., and Staubert, R.: 1985, *SSR* **40**, 371
Pounds, K. A., Cooke, B. A., Ricketts, M. J., Turner, M. J., and Elvis, M.: 1975, *MNRAS* **172**, 473
Pringle, J. E.: 1981, *ARAA* **19**, 137
Protheroe, R. J.: 1986, *Proc. ASA* **6**, 280
Protheroe, R. J.: 1987, *Proc. 20th Intern. Cosmic Ray Conf. (Moscow)* **8**, 21
Protheroe, R. J., and Clay, R. W.: 1985, *Nature* **315**, 205
Protheroe, R. J., and Stanev, T.: 1987a, *Nature* **328**, 136
Protheroe, R. J., and Stanev, T.: 1987b, *ApJ* **322**, 838
Protheroe, R. J., Clay, R. W., and Gerhardy, P. R.: 1984, *ApJ* **280**, L47
Rappaport, S., Clark, G. W., Cominsky, L., Joss, P. C., and Li, F.: 1978, *ApJ* **224**, L1
Raubenheimer, B. C., North, A. R., de Jager, O. C., and Nel, H. I.: 1989, *ApJ* **336**, 394
Robba, N. R., Cusumano, G., Orlandini, M., Dal Fiuma, D., and Frontera, F.: 1992, *ApJ* **401**, 685
Rose, L. A., et al.: 1979, *ApJ* **231**, 919
Rudak, B., and Meszaros, P.: 1991, *ApJ* **383**, 269
Seckel, D., Stanev, T., and Gaisser, T. K.: 1991, *ApJ* **382**, 652
Shakura, N. I., and Sunyaev, R. A.: 1973, *AAp* **24**, 337
Shapiro, S. L., and Teukolsky, S. A.: 1983, *Black Holes, White Dwarfs, and Neutron Stars*, Wiley: New York
Skinner, G. K., Shulman, S., Share, G., Evans, W. D., McNutt, D., Meekins, J., Smathers, H., Wood, K., Yentis, D., Byram, E. T., Chubb, T. A., and Friedman, H.: 1980, *ApJ* **240**, 619
Slane, P., and Fry, W. F.: 1989, *ApJ* **342**, 1129

Stecker, F. W.: 1970, *ApSS* **6**, 377
Stecker, F. W.: 1973, *ApSS* **20**, 47
Stecker, F. W.: 1979, *ApJ* **228**, 919
Stenger, V. J.: 1984, *ApJ* **284**, 810
Stepanian, A. A., Vladimirsky, B. M., and Fomin, V. P.: 1972, *Nature (Phys. Sci.)* **239**, 40
Stephens, S. A., and Badhwar, G. D.: 1981, *ApSS* **76**, 213
Suga, K., Toyoda, Y., Kamata, K., Murakami, K., LaPointe, M., Gaebler, J., Escobar, I., Saavedra, O., Domingo, V., Shibata, S., Akiyama, H., Takano, M., and Uchino, K.: 1987, *Proc. 20th Intern. Cosmic Ray Conf. (Moscow)* **1**, 277
Thornton, G. J., Edwards, P. G., Gregory, A. G., Patterson, J. R., Roberts, M. D., Rowell, G. P., and Smith, N. I.: 1991, *Proc. 22nd Intern. Cosmic Ray Conf. (Dublin)* **1**, 336
Tuohy, I. R., and Cruise, A. M.: 1975, *MNRAS* **171**, 33p
Vacanti, G.: 1990, *Lecture Notes in Physics* **391**, 147
Vestrand, W. T., and Eichler, D.: 1982, *ApJ* **261**, 251
Vladimirskii, B. M., Neshpor, Yu. I., Stepanian, A. A., and Fomin, V. P.: 1973, *Proc. 14th Intern. Cosmic Ray Conf.* , 111
van der Walt, D. J., Raubenheimer, B. C., de Jager, O. C., North, A. R., van Urk, G., and de Villiers, E. J.: 1987, *Proc. 20th Intern. Cosmic Ray Conf. (Moscow)* **1**, 303
Weekes, T. C.: 1988, *Physics Reports* **160**, 1
Weekes, T. C.: 1992, *SSR* **59**, 314
White, N. E.: 1978, *Nature* **271**, 38
White, N. E., and Holt, S. S.: 1982, *ApJ* **257**, 318
White, N. E., Mason, K. O., and Sanford, P. W.: 1978, *MNRAS* **184**, 67p

Figure Captions

Figure 1: Schematic sketch, to scale, of the orbits and companion stars of eight binary X-ray pulsars. The approximate mass of the companion star is indicated below each orbit (after Joss & Rappaport 1984).

Figure 2: A comparison of the very different geometries of a low-mass X-ray binary ($M_{\rm opt}/M_x \sim 1/12$) and a massive X-ray binary ($M_{\rm opt}/M_x \sim 12$). The optical star (cross hatched) is in each case filling its critical Roche lobe. The radial extent of the accretion disk around the neutron star (dotted) is outlined nearby to scale. The dots mark the center of mass of the individual stars, and crosses mark the mass centers of the systems (after Bradt & McClintock 1983).

Figure 3: The signal strengths for each observation of Vela X-1 as a function of orbital phase. The closed symbols indicate signal strengths that differ more than one standard deviation from zero. The hatched areas indicate the X-ray eclipse (after North et al. 1991a).

Figure 4: a) The signal strengths for each observation of Cen X-3 as a function of orbital phase (after North et al. 1991b). The closed symbols indicate signal strengths that differ more than one standard deviation from zero. The hatched area indicates the accretion wake. Also shown are the average signal strengths in the wake $(6.6 \pm 1.3)\%$ and out of the wake of $(1.4 \pm 0.4)\%$. The solid horizontal bar indicates those orbital phases where evidence for the emission of TeV γ-rays was found by the Durham group (Chadwick et al. 1990). The typical orbital phase coverage of an observation is ± 0.04. b) The recent pulse period history of Cen X-3 including the periods for the in-wake peak shown in Fig. 4a, for each year's observation.

Figure 5: Orbital phase of γ-emission from Cygnus X-3 (a) at energies below 100 TeV and (b) above 100 TeV (after Protheroe 1987).

Figure 6: Possible scenario of the VHE γ-ray production in X-ray binary pulsars (after Hillas 1987). (a) Atmosphere of the companion acts as a target, (b) an accretion wake, (c) a structure attached to an accretion disk.

Figure 7: Gamma-ray absorption length in thermal bremsstrahlung of the accretion disk corona of temperature 10^7 and 6×10^7K (after Protheroe & Stanev 1987b).

Figure 8: Transmission versus γ-ray energy for the six binary systems considered (after Carraminana 1992).

Figure 9: Her X-1 and 4U 0115+63 spectra resulting from pair absorption (after Carraminana 1992). Fluxes of photons are in arbitrary units; the tick distances along the vertical axes represent factors of ten. The straight lines show the input power law of slope 2.5, the dashed lines correspond to the spectra found considering only the absorption of primary VHE photons. The dashed-dotted lines are found when the pair-Compton cascade is taken into account, their "waviness" is due to fluctuations in the simulated cascades.

Figure 10: Geometry of a close binary system (after Moskalenko & Karakula 1994).

Figure 11: Phase of VHE radiation against the eccentricity of the relative orbit for some values of the longitude of periastron ω (after Moskalenko & Karakula 1994).

Figure 12: Calculated optical depth $\tau_{\gamma\gamma}$ against the product $\sin i \times \cos\psi$, for selected energies E_γ=0.1, 1, 10 and 100 TeV and two temperatures of the photon field, $kT = 3$ eV (solid line) and 4 eV (dashed line) (after Moskalenko & Karakula 1994).

Figure 13: The light curves of nine systems (after Moskalenko & Karakula 1994). The curves are $E_\gamma = 0.1$ TeV (heavy solid line), 1 TeV (solid line), 10 TeV (dashed line), and 100 TeV (dotted line). The values of parameters are listed in Table II.

Figure 14: Interaction length of γ-rays for pair production in the microwave background (after Protheroe 1986). Distances for a number of potential sources are indicated.

TABLE I
The source catalog (compiled by Weekes 1992).

Pulsars	X-ray binaries	Supernova remnants
PSR 0355+54	Her X-1	Crab Nebula
PSR 0531+21	Cyg X-3	
PSR 0833-45	Vela X-1	Extragalactic
PSR 1509-58	Sco X-1	Cen A
PSR 1953+29	SMC X-1	M 31
PSR 1937+21	LMC X-4	
PSR 1957+20	Cen X-3	Cataclysmic variables
PSR 1855+09	4U 0115+63	AE Aqr
	1E 2259+58	AM Her

TABLE II
The orbital parameters of the close binaries (after Moskalenko & Karakula 1994).

Object	$T^{a)}$ (K)	$kT^{b)}$ (eV)	R_c (cm)	a (cm)	e	i	ω
Cyg X-3$^{c)}$	30000	4	1.0×10^{11}	2.0×10^{11}	$0.5^{d)}$	$70°$	$-60°^{d)}$
SMC X-1$^{j)}$	30000	3	1.15×10^{12}	1.8×10^{12}	0	$62°$	-
Her X-1$^{e)}$	8000	1.8	2.84×10^{11}	4.0×10^{11}	0	$85°$	-
4U0115+63$^{h)}$	25000	3	7.0×10^{11}	4.47×10^{12}	0.34	$\leq 70°$	$47.7°$
Cen X-3	40000	4	8.53×10^{11}	1.27×10^{12}	0.001	$70°$	-
LMC X-4$^{k)}$	40000	4	6.3×10^{11}	8.5×10^{11}	0.006	$68°$	-
Vela X-1	25000	3	2.17×10^{12}	3.44×10^{12}	0.092	$80°$	$152°^{g)}$
4U1538-52$^{f)}$	40000	4	1.0×10^{12}	1.76×10^{12}	0.07	$70°$	$180°$
GX 301-2$^{i)}$	28000	3	3.1×10^{12}	1.17×10^{13}	0.47	$70°$	$-46°$

Notes
Most of parameters are taken from Joss & Rappaport (1984), here T is the temperature of the visible star obtained from its spectral class, kT is the effective temperature of the companion's surface, R_c is the radius of the companion star, a is the semi-major axis of the relative orbit, e is the eccentricity, i is the inclination angle, ω is the longitude of periastron.
a) Bradt & McClintock 1983; Allen 1973. *b*) Effective temperature of the photon field of the star including the effect of X-ray heating by the neutron star. *c*) parameters assumed by Moskalenko & Karakula 1994. *d*) Giler 1989. *e*) also Deeter et al. 1981. *f*) also Makishima et al. 1987. *g*) Deeter et al. 1987. *h*) Rappaport et al. 1978. *i*) Parkes et al. 1980; Kelley et al. 1980; White et al. 1978. *j*) also Levine et al. 1993. *k*) also Levine et al. 1991.

TABLE III

List of close binary systems (Nagase 1989; van der Klis 1989; Bhattacharya & van den Heuvel 1991).

Object	P_{rot} (s)	P_{orb} (days)	L_x (erg/s)	Type
Sco X-1	(0.005)	0.8	7×10^{37}	LMB
Cyg X-3	0.0126	0.2	8×10^{37}	HMB
SMC X-1	0.717	3.89	5×10^{38}	HMB
Her X-1	1.24	1.7	2×10^{37}	LMB
4U0115+63	3.61	24.3	3×10^{37}	HMB(Be)
Cen X-3	4.84	2.09	5×10^{37}	HMB
LMC X-4	13.5	1.41	4×10^{38}	HMB
Vela X-1	283	8.97	2×10^{36}	HMB
4U1538-52	529	3.73	4×10^{36}	HMB
GX 301-2	696	41.4	3×10^{36}	HMB

Notes
P_{rot} is the rotational period of the neutron star, P_{orb} is the orbital period of the binary system, L_x is the X-ray luminosity. High-mass binaries (HMB) and low-mass binaries (LMB) are marked, (Be) is the Be-star.